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# Time-dependent Mass Loss Rate Behavior of Wall Materials Under External Radiation

**Ellen G. Brehob and Anil K. Kulkarni**

The Pennsylvania State University, University Park, PA 16802, USA

**External radiation in enclosure fires can significantly enhance flame spread and fire growth. One of the effects of external radiation is to increase the mass loss rate of the fuel, which in turn produces larger flames. In this work, a measurement of mass loss with and without applied radiation was made as a function of time for three types of materials: a plastic (polymethylmethacrylate), wood-based products (particle board and hardboard), and a paper-based product (cardboard). The levels of applied radiation ranged from 0 to nearly 12 kW m$^{-2}$. The purpose of the investigation was to (1) quantitatively determine the effect of external radiation on the mass loss of various materials, (2) measure various parameters which may be used to characterize the mass loss rate history of the materials and (3) determine a method for expressing the mass loss rate as a function of time for input into numerical models. Higher levels of external radiation resulted in higher peak mass loss rates and quicker consumption of the material. Quantities which are useful for ranking the flammability of materials have been measured for the samples tested and are tabulated.**

## INTRODUCTION

In many enclosure and corridor fires the radiation from surrounding walls has a significant effect on fire growth and the spread rate of flames. Levels of radiant flux as high as 100 kW m$^{-2}$ are commonly found in post-flash-over enclosure fires,[1] but prior to full involvement of the enclosure, significantly lower radiation levels may be found. If a wall exposed to external radiation is ignited at the bottom, one of the effects of the external heat flux is enhanced burning rate of the ignited area, which causes larger flames and faster upward flame spread.[2] Models for predicting flame spread on burning surfaces require an accurate input of transient heat release rate at each location on the wall. Assuming that the heat release rate can be expressed as the mass loss rate multiplied by a constant heat of combustion, then the mass loss rate may be used in these models. For example, the model proposed by Saito *et al.*[3] is an example of the role mass loss rate plays in flame spread prediction. Heat feedback to the wall is the dominant mechanism in upward flame spread, and to model the feedback to the wall it is useful to determine the extent of the wall covered by flames. An equation for predicting the flame height is

$$x_f(t) - x_b(t) = K\left[\dot{Q}' + h_c \int_{x_p(t)}^{x_b(t)} \dot{m}'' \mathrm{d}x\right]^n \qquad (1)$$

where $x_f$ is the flame height, $x_p$ the pyrolysis height, $x_b$ the burnout height, $x$ the co-ordinate moving up the wall, $\dot{Q}'$ the igniter strength, and $K$ and $n$ experimentally determined constants. The transient mass loss rate is required in the equation to determine the heat release rate of the fuel. For fully involved walls, $\dot{m}''$ is a weak function of $x$; in upward flame spread, however, each vertical location ignites at a different time, causing $\dot{m}''$ to be strongly dependent on $x$. Accurate modelling of the fuel heat release rate and combining it with the igniter heat release rate can then be related to the flame height.

Smith and Green[4] designed a mathematical model for a developing fire in a compartment which required experimental heat release data. For their model the heat release rate was correlated with total heat released. The use of experimental data was encouraged by the authors, since the use of fundamental constants to express the heat release rate is presumed to be a long way off. The local mass loss rate is an input parameter for several numerical and theoretical models. In the work by Cleary and Quintiere[5] a model for predicting flame spread in various orientations was developed in terms of 'fire' properties of a material, measurable in small-scale experiments. The Karlsson and Magnusson[6] model for simulating room fires required an analytical approximation of the heat release rate as a function of time.

It has been shown by Kulkarni and Kim[7] that the transient nature of the local mass loss rate is indeed an important parameter required for accurate prediction of flame spread. Kulkarni *et al.*[8] investigated the transient local mass loss rate of vertical burning slabs of PMMA with no external radiation flux by comparing an experimental measurement with a theoretical prediction. For the non-charring material tested, agreement in the mass loss rates was good. Mitler[9] used both a mass loss rate based on a steady-state energy balance at the surface and one from experimental measurements in this model to predict pyrolysis front position with time. For a non-charring, non-melting material, the two mass loss rates yielded similar results, but the author suggested that the experimentally measured mass loss rate has the advantage of accounting for material thickness and charring. In the work done by Kim,[10] a numerical model was developed to predict upward flame spread which accepts experimentally measured mass loss rate, $\dot{m}''(t)$, as input. In an extension of this work, the effect of external radiation on upward flame spread, for which a measurement of the local mass rate with applied external radiation is required, is being investigated.

Previous work has demonstrated a need for accurate heat release rate (HRR) information, and various

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methods to obtain this information have been employed. The burning intensity of plastics and wood samples was measured by Tewarson and Pion.[11] Experimental measurements of mass loss rate were made for samples in a horizontal configuration with the capability to supply external radiation. Although mass loss was measured continually, only steady-state mass loss rates were presented. The authors concluded that use of the small-scale test apparatus was useful for measuring important thermo-physical properties of materials. Transient mass loss rates for particleboard and PMMA under external radiation have been measured by Vovelle *et al.*[12] In their experiments, samples were pyrolyzed in a vertical orientation, but no ignition flame was supplied. They found that the mass loss rates for PMMA, when properly scaled with radiant flux, tended to collapse onto the same curve. For a charring material such as particleboard, additional terms which give information on the density profile of the material must be included to obtain similar curves.

HRR, which can be related to mass loss rate, may also be measured for various materials under external radiation in the Cone Calorimeter.[1,13] Pilot flames are located above or on the face the sample, but do not cover the full face of the sample. Since relatively small samples (100 mm × 100 mm) are burned in the Cone Calorimeter, the measurement of transient HRR is based on a sample burning with predominantly laminar flames. Another widely used device for measuring heat release rate was designed at Ohio State University; this uses a thermopile to measure the temperature of the gases leaving the sample burning chamber.[14] The sample size used in this method is also relatively small (150 mm × 150 mm) and is ignited with an impinging pilot flame. The HRR and other parameters measured in the Cone and the OSU apparatus have been suggested as means of classifying the flammability of materials.

The specific objectives of the present work are to (1) measure mass loss history, which will be a unique characteristic of the material, under conditions similar to those encountered in the turbulent upward flame spread, (2) identify important time constants and 'fire properties' for each material which may be useful in characterizing material flammability and (3) obtain data which can be put into a suitable analytical form for use in numerical models.

## EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 1. The infra-red radiant panels can produce a maximum of 63kW m$^{-2}$ of radiant flux and are adjustable to lower levels. The heating elements in the panels reach temperatures upto 1088 K (1500°F) and are embedded in a ceramic material and covered with a Corning Vycor face plate. In the current configuration, the panels subjected the sample to a maximum radiant flux of nearly 12 kW m$^{-2}$, with a variation of less than 10% of the average heat flux over the exposed sample area. A 120 mm × 120 mm piece of sample material was flush-mounted in a panel of inert material and had a backing of the same inert material. The sample and holder were installed on one end of the balance arm. Mass loss of the sample was measured continuously by an

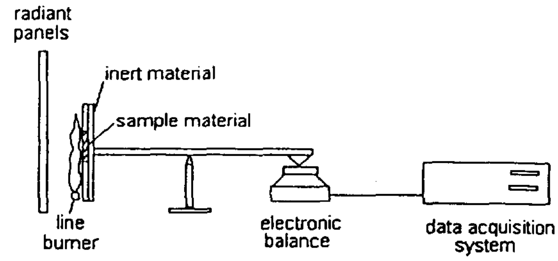


**Figure 1**. Experimental mass loss apparatus.

electronic balance, and the output voltage from the balance was fed into the data acquisition system. (Additional details of the mass loss apparatus are available in reference 10.) The samples were not preheated prior to ignition. In this set of tests, the radiant panels were preheated for 30 min, and during this time the sample material was shielded from the radiant flux. Nearly simultaneously, the radiant energy shield was removed, and the line burner placed in front of the sample.

The sample was exposed to flux from the radiant panels and uniformly covered by *turbulent flames* from a propane line burner. This method was adopted in order to simulate ignition and burning of the unburnt area above the flame front in a typical turbulent upward flame spread situation.

## DATA ANALYSIS

The voltage output from the balance was converted to units of mass loss per unit area, smoothed using an error detection routine, and corrected to account for the mass loss of the sample holder. A typical mass loss curve is shown in Fig. 2. Also denoted in the figure are the stages of burning. Mass loss versus time curves for some materials showed an initial preheat time during which no significant mass loss was measured. Following the preheat stage was a flaming combustion stage which exhibited significant mass loss. In the final stage, the glowing combustion stage, mass loss was fairly small, occurring at a steady rate for an extended period.

The quantities used to characterize the mass loss of a sample were the amount of time required for a given percentage of the consumable mass of the sample to be burned and the ignition time. (The consumable mass of the sample was determined by weighing the sample prior to testing, allowing the sample to fully burn, and then subtracting the weight of the ashes left.) For example, the time required for 25% of the sample's mass to be consumed may be determined easily from the graph of mass loss history. A quantity used by previous researchers for characterizing the flammability of a material is the peak mass loss rate and the time at which the mass loss rate peaks. Obtaining mass loss *rates* requires that the derivative with respect to time of the original data be taken. In order to do this, a fifth-order polynomial was used to fit the mass loss data after ignition, with mass loss rate forced to zero at $t=0$. The derivative of the polynomial was taken to obtain the mass loss rates, and then the peak mass loss rates was chosen.

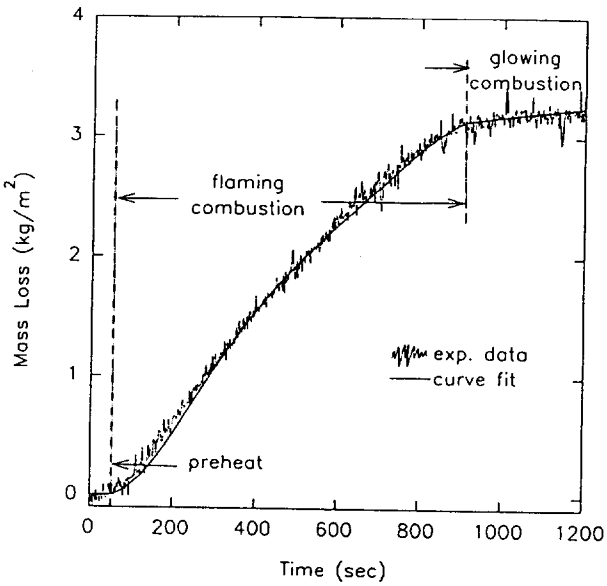


**Figure 2.** Mass loss for cardboard (with no external radiation) showing different regions of burning.

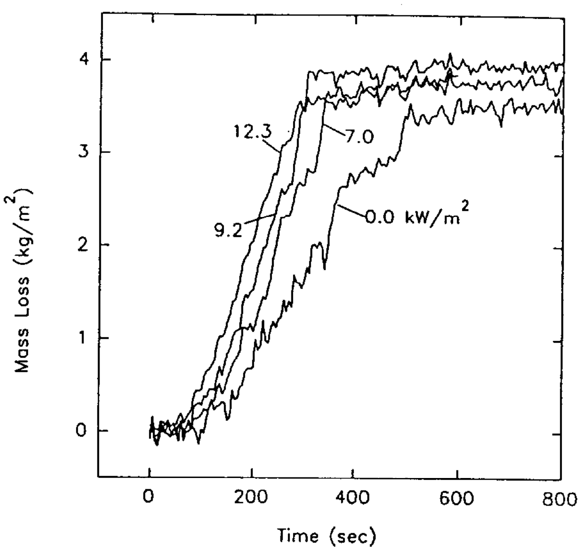


**Figure 3.** Mass loss curves for hardboard.

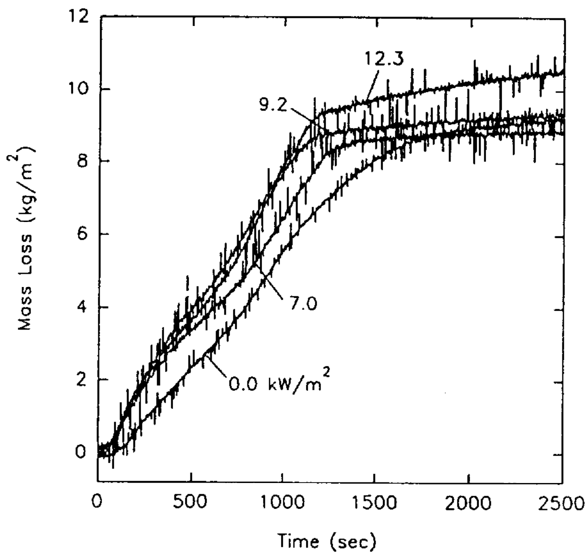


**Figure 4.** Mass loss curves for particle board.

## RESULTS AND DISCUSSION

Graphs of mass loss histories at four levels of external radiation for 3.2 mm hardboard and 15.9 mm particle board are shown in Figs 3 and 4. Mass was lost at a higher rate for higher levels of external radiation, and the samples burned out sooner at higher levels of external radiation. The trends observed in this plot are similar to those seen for the other materials tested, namely, 3.2 mm PMMA and 5.6 mm cardboard.

The data chosen for characterizing the mass loss of the various samples are ignition time ($t_{ign}$) and time for 25%, 50% and 75% of the consumable mass of the sample to be lost ($t_{25}$, $t_{50}$ and $t_{75}$, respectively). The data presented in Table 1 exhibit the general trend that decreasing amounts of time are required to consume a given percentage of a sample's mass as the level of external radiation is increased. Figure 5 is a plot of half-burnout time versus radiant flux level for each material. The plot shows the expected result that half-burnout time decreases with increasing radiant flux. The half-burnout time does not decrease in proportion to the increased flux levels, and therefore supplying higher levels of radiant flux would not be expected to proportionately enhance the mass loss rate of the samples tested.

From Table 1, PMMA showed the longest preheat times of the materials tested. PMMA, a plastic, has a well-defined ignition temperature that must be attained before pyrolysis begins. The other three materials (particle board, cardboard and hardboard) are cellulose-based materials which do not have well-defined ignition temperatures. Outgassing and pyrolysis for these materials occur over a range of temperatures.

Two other parameters commonly used to describe the flammability of a material are peak mass loss rate and time to peak. Table 2 lists the peak mass loss rates and time to peak as determined by the current set of tests and previous work. The peak mass loss rates increase with increasing levels of external radiation. Comparison with other works shows peak mass loss rates that are of the same order of magnitude, but are not directly comparable due to differences in testing (heat fluxes, sample thicknesses and ignition methods differ). In Fig. 6, the peak mass loss rate for each material is plotted versus the radiant flux level, which demonstrates a general increase in peak mass loss rate with an increase in external radiation.

In Fig. 7, data obtained from the Cone Calorimeter (Parker[14]) and the OSU apparatus (Tran[15]) are compared with the current data. (Selected data points were chosen for presentation in this paper in order to give the correct shape of the curve, but not the full detail of the experimental data.) The heat release rate for a fuel is determined with the Cone Calorimeter by measuring the oxygen consumption rate of the fuel. The heat release rate (HRR) may be converted to mass loss rate by assuming a

**Table 1. Characteristic times associated with mass loss curves**

| Material | $\dot{q}''_{er}$ (kW m$^{-2}$) | $t_{ign}$ (s) | $t_{25}$ (s) | $t_{50}$ (s) | $t_{75}$ (s) |
|---|---|---|---|---|---|
| Hardboard (3.2 mm) | 0.0 | 80 | 213 | 311 | 390 |
| Hardboard (3.2 mm) | 7.0 | 35 | 178 | 239 | 305 |
| Hardboard (3.2 mm) | 9.2 | 0 | 158 | 213 | 276 |
| Hardboard (3.2 mm) | 12.3 | 0 | 130 | 180 | 238 |
| PMMA (3.2 mm) | 0.0 | 136 | 280 | 368 | 466 |
| PMMA (3.2 mm) | 7.0 | 90 | 186 | 243 | 296 |
| PMMA (3.2 mm) | 9.2 | 50 | 154 | 207 | 255 |
| PMMA (3.2 mm) | 12.3 | 68 | 149 | 197 | 240 |
| Cardboard (5.6 mm) | 0.0 | 43 | 290 | 560 | 1038 |
| Cardboard (5.6 mm) | 7.0 | 51 | 194 | 386 | 700 |
| Cardboard (5.6 mm) | 9.2 | 42 | 184 | 362 | 636 |
| Cardboard (5.6 mm) | 12.3 | 30 | 162 | 314 | 512 |
| Particle board (15.9 mm) | 0.0 | 0 | 610 | 1030 | 2200 |
| Particle board (15.9 mm) | 7.0 | 0 | 420 | 930 | 1430 |
| Particle board (15.9 mm) | 9.2 | 0 | 380 | 806 | 1380 |
| Particle board (15.9 mm) | 12.3 | 0 | 354 | 780 | 1124 |

**Table 2. Peak mass loss rates**

| Material | Reference | Thickness (mm) | $t_{peak}$ (s) | $\dot{m}''_{peak}$ (kg m$^{-2}$ s) | Sample mass (g) | $\dot{q}''_{er}$ (kW m$^{-2}$) |
|---|---|---|---|---|---|---|
| Hardboard | | 3.2 | 250 | $10.7 \times 10^{-3}$ | 53.6 | 0.0 |
| Hardboard | | 3.2 | 260 | $16.4 \times 10^{-3}$ | 53.6 | 7.0 |
| Hardboard | | 3.2 | 245 | $19.2 \times 10^{-3}$ | 53.6 | 9.2 |
| Hardboard | | 3.2 | 195 | $18.4 \times 10^{-3}$ | 53.6 | 12.3 |
| Hardboard | 16[b] | — | — | $11.1 \times 10^{-3}$ | — | 25.0 |
| Hardboard | 16[a] | — | — | $25.7 \times 10^{-3}$ | — | 20.0 |
| Hardboard | 16[c] | — | — | $24.5 \times 10^{-3}$ | — | 25.0 |
| PMMA | | 3.2 | 322 | $10.3 \times 10^{-3}$ | 50.6 | 0.0 |
| PMMA | | 3.2 | 216 | $16.7 \times 10^{-3}$ | 50.6 | 7.0 |
| PMMA | | 3.2 | 190 | $16.4 \times 10^{-3}$ | 50.6 | 9.2 |
| PMMA | | 3.2 | 170 | $19.8 \times 10^{-3}$ | 50.6 | 12.3 |
| PMMA | 1 | 25.0 | — | $14.6 \times 10^{-3}$ | — | 35.0 |
| PMMA | 1 | 25.0 | 810 | $41.4 \times 10^{-3}$ | — | 75.0 |
| Cardboard | | 5.6 | 240 | $5.4 \times 10^{-3}$ | 61.7 | 0.0 |
| Cardboard | | 5.6 | 166 | $8.5 \times 10^{-3}$ | 61.7 | 7.0 |
| Cardboard | | 5.6 | 146 | $8.9 \times 10^{-3}$ | 61.7 | 9.2 |
| Cardboard | | 5.6 | 148 | $9.9 \times 10^{-3}$ | 61.7 | 12.3 |
| Particle board | | 15.9 | 622 | $6.8 \times 10^{-3}$ | 171.5 | 0.0 |
| Particle board | | 15.9 | 230 | $9.1 \times 10^{-3}$ | 171.5 | 7.0 |
| Particle board | | 15.9 | 208 | $9.9 \times 10^{-3}$ | 171.5 | 9.2 |
| Particle board | | 15.9 | 230 | $10.5 \times 10^{-3}$ | 171.5 | 12.3 |
| Particle board | 4 | — | — | $9.9 \times 10^{-3}$ | — | 20.0 |
| Particle board | 14 | 12.7 | 50 | $15.8 \times 10^{-3}$ | — | 50.0 |
| Particle board | 15[b] | 13.0 | 120 | $14.2 \times 10^{-3}$ | — | 35.0 |
| Particle board | 15[c] | 13.0 | 120 | $16.7 \times 10^{-3}$ | — | 35.0 |
| Particle board | 17 | — | — | $13.5 \times 10^{-3}$ | 5100 | 25.0 |

[a] data obtained using the Cone Calorimeter, $O_2$ consumption method.
[b] data obtained using the thermopile method, OSU apparatus.
[c] data obtained using the $O_2$ consumption method, OSU apparatus.
All mass loss rates reported from previous research were obtained from rate of heat release data by using a constant heat of combustion. The heat of combustion values used were: hardboard ($h_c = 15000$ kJ kg$^{-1}$), PMMA ($h_c = 25600$ kJ kg$^{-1}$) and particle board ($h_c = 11600$ kJ kg$^{-1}$).

constant heat of combustion,

$$\mathrm{HRR} = \dot{m}''(t) \times h_c \tag{2}$$

For particle board a value of $h_c = 12\,000$ kJ kg$^{-1}$ was used.[14] The Cone Calorimeter data were taken with a radiant flux level of 50 kW m$^{-2}$. Therefore, the resulting mass loss rate curve is much steeper and burnout occurs much earlier than in the current data which was taken at a maximum of 12.3 kW m$^{-2}$. Note also that the data from the Cone Calorimeter were measured for 12.7 mm thick particleboard, and the current data was taken for 15.9 mm thick particleboard. Because the area under each mass loss rate curve corresponds to the combustible mass per unit area of the sample, the area under the Cone Calorimeter curve is less. The sample burned in the Cone was mounted in a vertical position with an insulated back

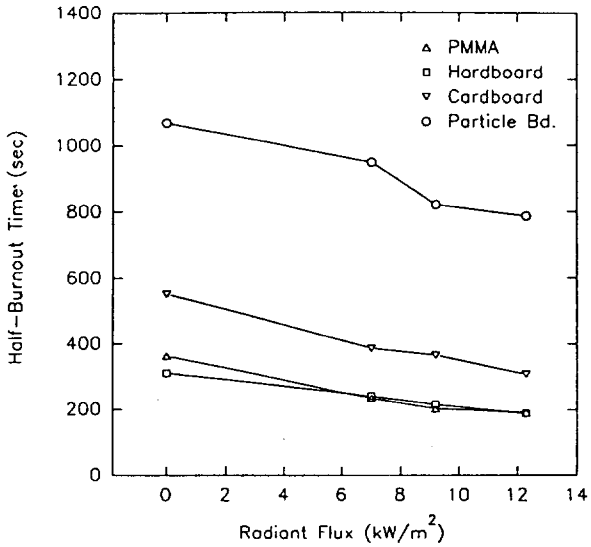


Figure 5. Half-burnout time as a function of external radiation.

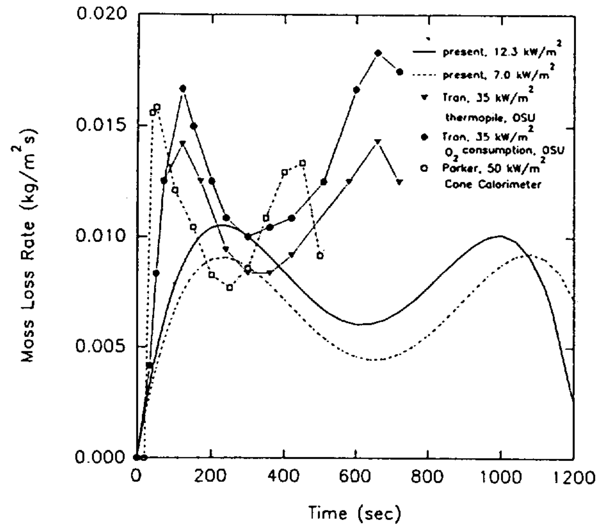


Figure 7. Mass loss rate for particle board measured in various experiment.

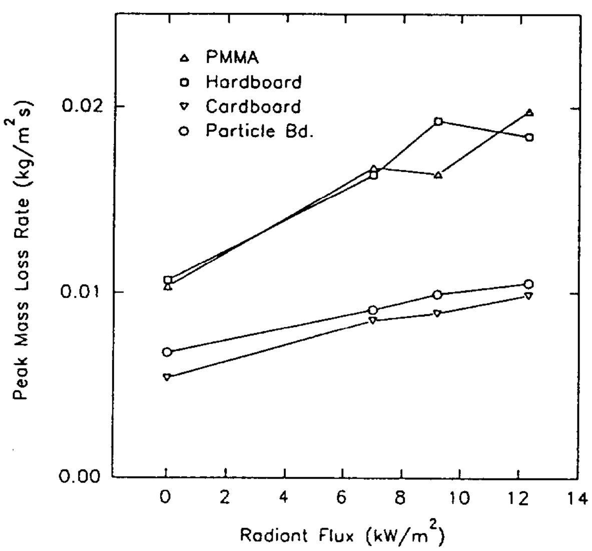


Figure 6. Peak mass loss rate as a function of external radiation.

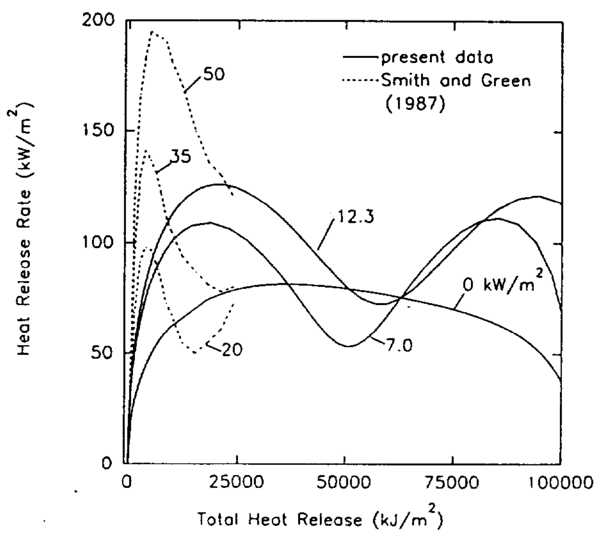


Figure 8. Heat release rate plotted against total heat release for particle board.

face. The OSU data were taken at an external radiant flux of 35 kW m$^{-2}$, and the sample was 13 mm thick. Although all samples were particle board, variations in materials and moisture content of the samples may also contribute to differences in the data. However, all methods for obtaining mass loss rate curves with external radiation (Vovelle *et al.*;[12] Parker;[14] Tran;[15] and the present work) resulted in the two-peak shape.

The two materials that were tested and exhibited the two-peak shape were particle board and cardboard. Both are charring materials, and the second peak may be the result of either the formation of a char layer which alters heat transfer to the deeper material or of outgassing of volatile materials decreasing while another part of the material has reached its pyrolysis temperature. Hardboard, also a cellulose-based material, did not show the two peak behavior. Since the hardboard sample was thinner than the other two cellulose-based materials, perhaps an inhibiting char layer was not able to form and the whole thickness of the material was pyrolyzed quickly.

An alternate method to present heat release data was used by Smith and Green.[4] These researchers correlated the heat release rate with the total heat release of the sample, which was a useful form for their numerical model. By properly manipulating the current data, a comparison of this data with the Smith and Green data is presented in Fig. 8. Information on the sample thickness was not available, which may account for the different scales of total heat release in the current data and those of Smith and Green. Many flame spread models require the input of heat release rate (or mass loss rate) histories, and therefore, the focus of the present work is the presentation of data as a function of time.

## SUMMARY AND CONCLUSIONS

Experimental measurements of transient mass loss rates for hardboard, PMMA, cardboard and particle board at various levels of radiation up to 12.3 $kW\,m^{-2}$ were made in a configuration most similar to a turbulent upward flame-spread configuration. These data can be expressed in an analytical form useful for numerical models.

As expected, the mass loss rate increases with increasing external radiation and the half-burnout time decreases with increasing external radiation. For cardboard and particle board, the two-peak mass loss rate curve was observed, which is similar to the results obtained by previous investigators.

### Acknowledgement

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